

Hydrothermal carbonization (HTC) of green waste: Mitigation potentials, costs, and policy implications of HTC coal in the metropolitan region of Berlin, Germany

Jakob Medick^{a,1}, Isabel Teichmann^{a,*}, Claudia Kemfert^{a,b}

^a German Institute for Economic Research (DIW Berlin), Mohrenstraße 58, 10117 Berlin, Germany

^b Hertie School of Governance (HSOG), Friedrichstraße 180, 10117 Berlin, Germany

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ABSTRACT

We quantify the greenhouse-gas mitigation potential and carbon abatement costs if green waste in the metropolitan region of Berlin, Germany, is diverted from composting into the production of hydrothermally carbonized coal (HTC coal) that is used to substitute for hard coal in electricity and heat generation. Depending on the origin of the green waste, we specify an urban, a rural-urban, and a rural scenario. All scenarios combined can mitigate 70,511 metric tons (t) of carbon-dioxide equivalents (CO₂e) per year. The carbon abatement costs reach 163 €/t CO₂e in the urban scenario, 76 €/t CO₂e in the rural-urban scenario, and 77 €/t CO₂e in the rural scenario. The lower abatement costs in the latter two scenarios are mainly due to HTC-coal co-firing in an existing power plant rather than constructing a new biomass power plant for HTC-coal mono-firing as in the urban scenario. While the abatement costs exceed the current carbon prices, they compare more favorably with commonly assumed damage costs of unmitigated climate change. Thus, the public support of HTC coal could be considered, with the primary policy focus on HTC-coal co-firing. HTC-coal co-firing could also lower the emissions of existing power plants during the fossil-fuel phase-out.

1. Introduction

Biomass is a controversial source of renewable energy. On the one hand, energy crops are highly debated for their role in food security and greenhouse-gas (GHG) emissions from land-use change (e.g., Rosegrant and Msangi, 2014; Searchinger et al., 2009). For electricity generation, on the other hand, biomass has the advantage of being dispatchable (e.g., Neuhoﬀ et al., 2016). Thus, it can contribute to reduced power storage and system costs in an electricity-generation system that is dominated by fluctuating renewables, such as solar and wind energy (Schill and Zerrahn, 2018).

In addition to biomass residues, these considerations have strengthened the focus on biogenic waste, such as municipal green waste (e.g., leaves and grass cuttings), for electricity generation. However, there are limits to the potentials of biogenic waste (see, e.g., Brosowski et al., 2016 for Germany). Moreover, such feedstocks are

often characterized by high water contents, low heating values, and heterogeneous quality (e.g., Libra et al., 2011), which renders them unsuitable for direct biomass combustion and possibly even anaerobic digestion. Thus, the use of biogenic waste for electricity generation relies on efficient conversion technologies. One such promising technology is hydrothermal carbonization (HTC) (e.g., Titirici et al., 2007; Funke and Ziegler, 2010; Libra et al., 2011).

HTC is a thermochemical conversion process that transforms biomass into a carbon-rich, coal-like product – HTC coal (or biocoal, hydrochar) – and some gaseous – mainly carbon dioxide (CO₂) – and liquid by-products (for more details, see Section S.1 in the Supplementary material).² HTC coal can be co-fired in conventional coal power plants or mono-fired in combined-heat-and-power (CHP) biomass plants. Since HTC typically requires biomass with a water content of 75–90% (Libra et al., 2011: 98), it can transform wet feedstocks into solid fuels without energy-intensive pre-drying.³ Compared

Abbreviations: a, year; CH₄, methane; CHP, combined heat and power; CO₂, carbon dioxide; CO₂e, carbon-dioxide equivalent; FM, fresh matter; FM_{prep}, prepared fresh matter; GHG, greenhouse gas; HTC, hydrothermal carbonization; LCA, life-cycle assessment; N₂O, nitrous oxide

* Corresponding author.

E-mail addresses: medick@dw-eco.com (J. Medick), iteichmann@diw.de (I. Teichmann), ckemfert@diw.de (C. Kemfert).

¹ Present address: DWR eco GmbH, Albrechtstraße 22, 10117 Berlin, Germany.

² All sections, tables, and figures with the leading 'S.' can be found in the Supplementary material online.

³ HTC coal can be mechanically dewatered relatively easily before it is further dried (e.g., Ramke et al., 2012).

to direct biomass combustion, HTC coal is associated with reduced slagging and fouling (Reza et al., 2014) as well as increased maximum weight loss rates, higher ignition temperatures, and elevated combustion temperature regions (e.g., Liu et al., 2013). As a more homogenous fuel with a higher energy density, HTC coal is also easier to handle than the original biomass during transport, storage, and combustion. For certain types of biogenic waste, HTC can be even more suitable for energy recovery than anaerobic digestion. Leaves, for example, yield only a very low amount of methane (CH_4), 15–25 m^3 per metric ton (t) of fresh-matter (FM) input (ICU, 2011: 14). While associated with higher yields of 90 m^3 CH_4 /t FM input (ICU, 2011: 14), the utilization of grass cuttings for anaerobic digestion might involve technical difficulties, such as increased abrasion, increased stirring requirements, and frequent removals of sediment (Prochnow et al., 2009).

For all these favorable technical aspects, the use of HTC coal as a source of renewable energy from biogenic waste may represent an innovative GHG mitigation measure. However, before its large-scale implementation or even public support, a thorough assessment of the GHG mitigation potential and costs of HTC coal is needed. For this purpose, we provide a case study for the metropolitan region of Berlin, Germany, in which we focus on leaves and grass cuttings as inputs for the HTC process. The metropolitan region of Berlin is chosen as an example of a densely populated and, thus, emission-intensive area. The green waste from this region may become available for HTC since it is planned to recover its energy value; currently, it is usually composted (Schwilling et al., 2011). Our evaluation of HTC coal is based on its annual GHG mitigation potential, obtained from a life-cycle assessment (LCA), and its carbon abatement costs, i.e. the costs to mitigate a unit of CO_2e equivalents (CO_2e).

We present three scenarios that are not mutually exclusive. They are differentiated by the geographical origin of the green waste (urban, rural-urban, and rural). Consequently, they also differ by other parameters, such as the location of the HTC plant or the site and mode of HTC-coal combustion. The green waste for HTC is diverted from composting and the subsequent soil application of the compost to replace mineral fertilizers. The HTC coal, in pulverized form, substitutes for hard coal in electricity and heat generation.⁴

While we provide a case study for a relatively narrow region, our approach serves to embed the HTC scenarios in a realistic setting. In particular, the HTC scenarios are tailored to existing actors in the region's waste-management and energy sectors. For the location of the HTC plants and the logistics concepts for biomass transportation, preparation, and storage, we further take account of current infrastructure that can be utilized under the HTC system. Our data for the HTC process refer to an industrial-scale demonstration plant developed by *SunCoal Industries GmbH* (*SunCoal*), a manufacturer of HTC systems in Ludwigsfelde, Brandenburg.

We obtain the greatest GHG mitigation potentials per year (a) and the lowest abatement costs in the rural-urban (22,532 t $\text{CO}_2\text{e}/\text{a}$, 76.1 €/t CO_2e) and rural (25,749 t $\text{CO}_2\text{e}/\text{a}$, 77.2 €/t CO_2e) scenarios; the urban scenario has the lowest GHG mitigation potential (22,230 t $\text{CO}_2\text{e}/\text{a}$) and highest abatement costs (162.7 €/t CO_2e). With positive GHG mitigation potentials in all scenarios, our results indicate, first, that the substitution of fossil coal by HTC coal derived from green waste is an effective GHG mitigation measure. Second, while all scenarios' abatement costs exceed the current CO_2 prices in the European Union Emissions Trading System, below 17 €/t CO_2 (EEX, 2018), they compare more favorably with the damage costs of unmitigated climate change, which are not fully internalized in the CO_2 prices. Third, it is more efficient to substitute for fossil coal by co-firing the HTC coal in an existing coal-fired CHP plant (rural-urban and rural scenarios) than to

invest in a new biomass CHP plant for HTC-coal mono-firing (urban scenario). Fourth, the green waste we consider has to be collected and disposed of in any case. Thus, abatement costs of more than 76 €/t CO_2e at zero feedstock costs show that HTC can play a role as a GHG mitigation measure particularly if it is co-used as a waste-management technology.

Our analysis contributes to the environmental, economic, and policy literature on HTC coal for energy generation. In particular, economic and policy-relevant studies for HTC coal are still rare and largely rely on simulations of industrial-scale HTC plants derived from laboratory-scale data (e.g., Eberhardt et al., 2011; Erlach et al., 2011; Wirth et al., 2012; Stemmann et al., 2013a). Similar to our analysis, Eberhardt et al. (2011), Erlach et al. (2011), as well as Stemmann et al. (2013a) find that HTC coal cannot compete with fossil coal at market-based CO_2 prices. The literature further finds that the production costs of HTC coal tend to depend strongly on feedstock costs, with shares of up to 50% (Erlach et al., 2011; Eberhardt et al., 2011). However, these results are not directly comparable to our study, where the green waste is available at zero cost. According to Erlach et al. (2011), the production costs of HTC coal derived from poplar wood chips can be reduced slightly if the HTP plant is integrated with a wood-fired CHP plant. Our urban and rural-urban HTC scenarios incorporate similar synergy effects with a waste-incineration plant and a CHP plant, respectively.

2. Methodology

Based on an LCA, we provide the GHG mitigation potential and carbon abatement costs of HTC coal under three scenarios in the metropolitan region of Berlin, Germany. The metropolitan region of Berlin, as defined in our study, comprises all Berlin city districts plus the adjacent rural counties of Brandenburg/Havel, Havelland, Potsdam, Potsdam-Mittelmark, and Teltow-Fläming, located in the federal state of Brandenburg, southwest of Berlin. As input material into the HTC process, we focus on leaves and grass cuttings.

2.1. Scenarios

Differentiated by the geographical origin of the feedstocks, we design an urban, a rural-urban, and a rural HTC scenario. The urban HTC scenario draws on leaves and grass cuttings from the Berlin city districts that are collected by the public waste-management company *Berliner Stadtreinigung (BSR)* and by parks departments (Table 1). The rural-urban HTC scenario, in turn, uses leaves and grass cuttings collected by private gardening and landscaping firms in the Berlin city districts and grass cuttings from three counties in Brandenburg, while the rural HTC scenario relies exclusively on grass cuttings from two counties in Brandenburg. Since the three HTC scenarios use different biomass resources, they can be realized simultaneously.

In each scenario, we assume that the HTC plant has an annual throughput of 55,000 t prepared and purified FM input (FM_{prep}). This corresponds to the approximate capacity of the HTC demonstration plant developed by *SunCoal* (*SunCoal*, unpublished data). Since leaves and grass cuttings contain different proportions of inorganic material, such as stones, plastics, glass, and sand (Table S.1), the scenarios require different amounts of initial FM inputs to obtain 55,000 t $\text{FM}_{\text{prep}}/\text{a}$. In particular, the urban scenario uses 73,701 t FM/a, the rural-urban scenario 75,621 t FM/a, and the rural scenario 81,361 t FM/a (Table 1). These FM inputs are all covered by the available biomass potentials (Medick et al., 2017: Table 1).

In addition to the biomass sources, the three scenarios make different assumptions for the site and operator of the HTC plant, the site and mode of HTC-coal firing, the site for biomass preparation and storage, as well as the corresponding transport stages (Table 1). A detailed description of the logistics concepts can be found in Section S.2.

Managing most of the urban feedstocks, the assumed operator of the HTC plant in the urban HTC scenario is *BSR*. The HTC plant is located at

⁴ In 2013, 50.5% of Berlin's electricity was provided by hard coal, and 7.5% by lignite; the respective numbers for district heat were 23.6% and 16.7% (Amt für Statistik Berlin-Brandenburg, 2016: Tables 3.6 and 3.9).

Table 1
Key Scenario Assumptions.
Source: Own assumptions. Note: Values rounded.

	Urban HTC scenario	Rural-urban HTC scenario	Rural HTC scenario
Biomass sources	Leaves and grass cuttings from Berlin city districts (collected by BSR and parks departments)	- Leaves and grass cuttings from Berlin city districts (collected by private gardening and landscaping firms) - Grass cuttings from Brandenburg/Havel, Havelland, and Potsdam, Brandenburg	Grass cuttings from Potsdam-Mittelmark and Teltow-Fläming, Brandenburg
HTC-plant capacity	55,000 t FM _{prep} /a	55,000 t FM _{prep} /a	55,000 t FM _{prep} /a
FM biomass inputs	73,701 t FM/a	75,621 t FM/a	81,361 t FM/a
Share of urban leaves	74.4%	13.0%	0%
Share of rural grass cuttings	25.6%	18.7%	0%
Share of rural grass cuttings	0%	68.3%	100%
Site and operator of HTC plant	Waste-incineration plant Ruhleben, Berlin; BSR	Reuter West CHP plant, Berlin; Vattenfall	Composting facility in Jühnsdorf, Brandenburg
Mode and site of HTC-coal combustion	Mono-firing in new biomass CHP plant located at HTC plant Hennickendorf, Brandenburg	Co-firing in existing Reuter West CHP plant Ahrensfelde, Brandenburg/Havel, Nauen, and Potsdam, Brandenburg	Co-firing in existing Reuter West CHP plant Ludwigsfelde and Werder, Brandenburg
Biomass preparation and storage			
Transport stages	- BSR leaf sacks → Transfer points - Fresh biomass → Preparation-and-storage site - Prepared biomass → HTC plant	- Fresh biomass → Preparation-and-storage sites - Prepared biomass → HTC plant	- Fresh biomass → Preparation-and-storage sites - Prepared biomass → HTC plant - HTC coal → Reuter West CHP plant

the site of BSR's existing inner-city waste-incineration plant in Ruhleben, Spandau district (Figure S.1). In this way, the electricity provided by the waste-incineration plant can be used in the HTC process (for HTC-coal drying), increasing the efficiency of HTC-coal production. At the same site, a new biomass CHP plant is built by BSR for HTC-coal mono-firing. Due to a lack of urban storage space, the biomass for the HTC process is prepared and stored outside Berlin. The logistics concept comprises three biomass transport stages, which result from the external biomass preparation and storage as well as from different collection modes for the urban feedstocks (Section S.2).

In the rural-urban HTC scenario, the HTC plant is operated by the energy company Vattenfall, at the site of its existing inner-city coal-fired Reuter West CHP plant (Figure S.2). The co-location enables the HTC process to use electricity from the CHP plant (for HTC-coal drying). Moreover, this is also the site where the HTC coal is co-fired with conventional hard coal to replace the fossil fuel. The selected CHP plant uses a pulverization coal-firing system and, thus, is highly suitable for HTC-coal dust, as considered in our study. The biomass for the HTC process is prepared and stored at different locations outside Berlin. However, only two biomass transport stages are involved due to easier biomass collection modes.

In the rural HTC scenario, the HTC plant is operated outside Berlin, by a composting facility in Jühnsdorf (Figure S.3), one of the largest in the region (Rettenberger et al., 2012: 283). The HTC coal is co-fired at Vattenfall's inner-city Reuter West CHP plant. The biomass is prepared and stored at two locations in Brandenburg. The logistics concept comprises two stages, one for the biomass transport and another one for the HTC-coal transport.

Since most of the leaves and grass cuttings in- and outside Berlin are currently used for composting (Schwilling et al., 2011), each HTC scenario's reference case corresponds to feedstock composting and the subsequent soil application of the compost to substitute for mineral fertilizers. To reach system equivalence (cf. Rehl and Müller, 2013), the reference scenarios further consider the generation of electricity and heat from hard coal. We assume that HTC coal substitutes for hard-coal combustion at the Reuter West CHP plant. For consistency reasons, this holds even in the reference case of the urban HTC scenario, where the HTC coal is not directly used at the Reuter West CHP plant, but mono-fired at a new biomass CHP plant.

2.2. Life-cycle stages and system boundaries

The life-cycle stages and system boundaries for the three HTC scenarios and their reference cases are detailed in Fig. 1.

The left-hand side of Fig. 1 illustrates the life-cycle stages of the HTC system. First, the biomass collection takes place. This stage is neither ascribed with emissions nor with costs since the green waste we consider must be collected and disposed of in any case. Second, the biomass is bundled and transported to the respective preparation-and-storage sites (Table 1; Section S.2). Biomass preparation takes place before storage and comprises the screening, sieving, separating, and crushing of the fresh input material. To eliminate biomass losses during storage, the prepared biomass is baled and covered with foil. After storage, the biomass is transported to the respective HTC plant, where it is converted into pulverized HTC coal. Finally, the HTC coal is distributed to the combustion site for energy generation.

For composting in the reference system (right-hand side of Fig. 1), we consider the biomass transportation and preparation, activities accompanying the curing process (turning, screening, and blending), and the distribution, soil application, and mineralization of the compost (in substitution for mineral fertilizers). The logistics concepts for biomass and compost transportation are less sophisticated than those for HTC (Section S.3.2). We assume open-windrow composting, as predominant in the surroundings of Berlin (Vogt et al., 2012). The life-cycle stages for the generation of electricity and heat from hard coal, in turn, include all the extractive, transport-related, and conditioning efforts to

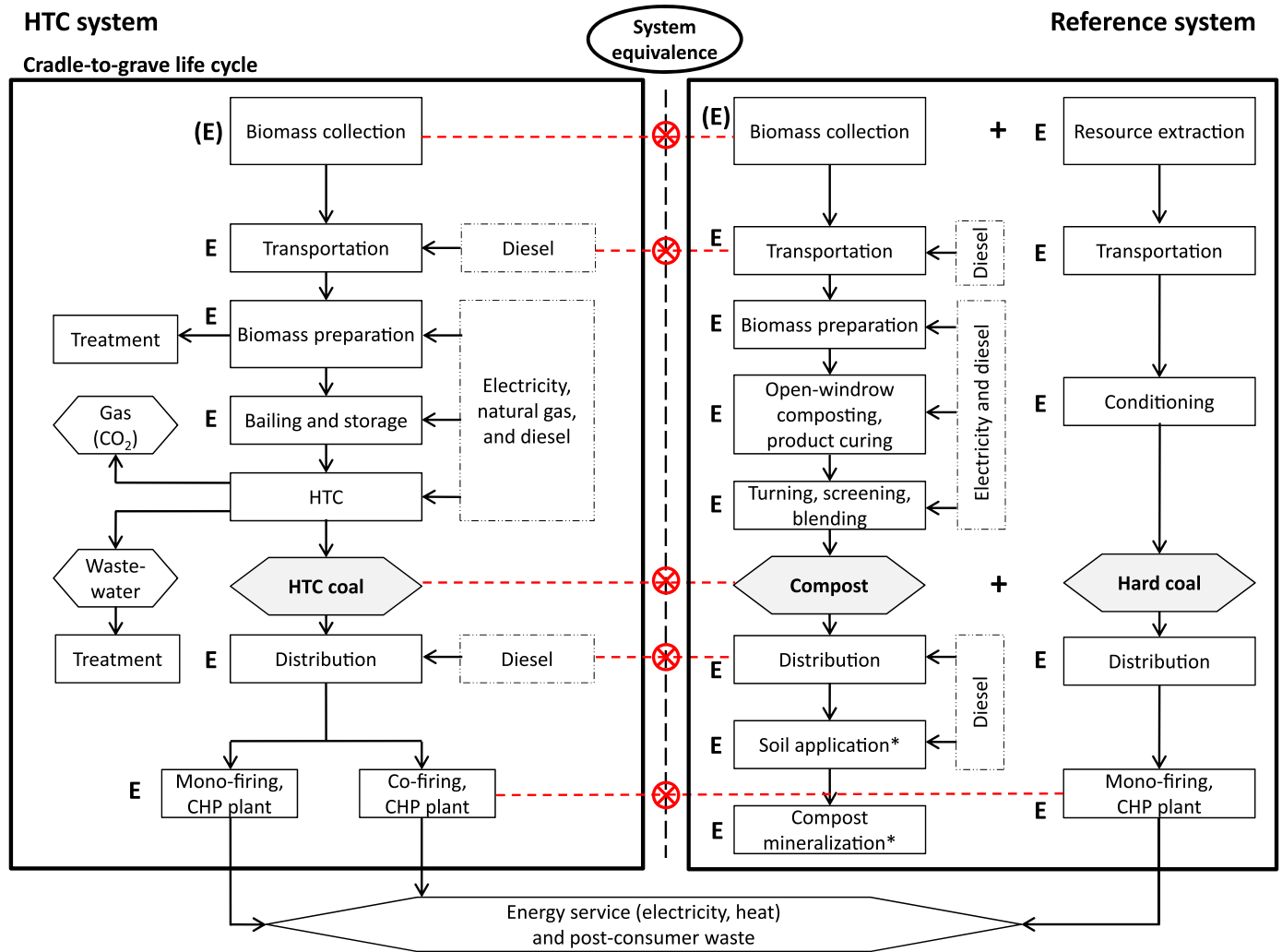


Fig. 1. Life-cycle stages and system boundaries of the HTC and reference systems.

Sources: Own illustration, adapted from Rehl and Müller (2013: 17); Cherubini (2010: 1569); Roberts et al. (2010: 828); NSW Department of Environment and Conservation (2007: 24). Notes: The crosses indicate parallel life-cycle stages or procedures within the HTC and reference systems. * = In substitution for mineral fertilizers (including upstream emissions). E = Emissions released along the life cycle.

provide the hard coal (i.e. all pre-combustion efforts), as well as the distribution and combustion of the fossil fuel.

In terms of emission sources, we focus on variable inputs of electricity, heat (natural gas), and diesel, not ascribing any GHG emissions to the construction of the HTC plants, composting facilities, and power plants. Regarding costs, we abstract from any administrative costs, rents, insurance payments, and taxes. Moreover, we do not include any costs and revenues that do not differ between a given HTC scenario and its reference case, such as biomass tipping fees. In the reference scenarios, we do not cover any costs for the soil application of the compost, assuming that they are about similar to the costs for the soil application of mineral fertilizers.

2.3. GHG mitigation potential and carbon abatement costs

The total GHG emissions along the life cycle of a given HTC scenario, E_{HTC} , and its reference case, $E_{Reference}$, are measured both in specific terms, kilogram (kg) CO₂e/t FM input, and on an annual basis, t CO₂e/a.⁵ The latter are obtained by multiplying the former by the annual biomass input from Table 1 (t FM/a), divided by 1000. The difference $E_{Reference} - E_{HTC}$ in the total annual GHG emissions refers to the

GHG mitigation potential of HTC coal (t CO₂e/a).

The carbon abatement costs, AC (€/t CO₂e), are calculated as follows (McKinsey, 2009):

$$AC = \frac{C_{HTC} - C_{Reference}}{E_{Reference} - E_{HTC}}, \text{ if } E_{Reference} - E_{HTC} > 0 \quad (1)$$

where C_{HTC} denotes the total annual net costs (€/a), i.e. costs minus revenues, obtained along the life cycle of an HTC scenario and $C_{Reference}$ those of the corresponding reference case. The denominator reflects the GHG mitigation potential of HTC coal (t CO₂e/a).

For use in the AC calculation, the initial investment costs for an HTC plant (and, in the urban HTC scenario, the biomass CHP plant) are annualized by multiplication with the annuity factor $AF = (1 + i)^T i / [(1 + i)^T - 1]$. We assume a time horizon of $T = 20$ years and a discount rate of $i = 6.5\%$. The discount rate is defined as the weighted average cost of capital, i.e. $i = (i_{equity} \text{Equity} + i_{debt} \text{Debt}) / (\text{Equity} + \text{Debt})$, where i_{equity} is the equity interest rate (%), i_{debt} is the debt interest rate (%), Equity is the total amount of equity (€), and Debt is the total amount of debt (€). While i_{debt} is oriented at the average rate of 4% offered for renewable-energy projects in Germany (KfW, 2017), we assume $i_{equity} = 9\%$. For simplicity, we use an equal share of debt and equity. In Section 4.3, we provide a sensitivity check for the discount rate i .

⁵ Note that we omit any scenario-related index in the variables we use.

Table 2

Life-cycle emissions.

Sources: Own calculations.

GHG emissions	HTC scenarios			Reference scenarios		
	Urban	Rural-urban	Rural	Urban	Rural-urban	Rural
	kg CO ₂ e/t FM input			kg CO ₂ e/t FM input		
Transportation ^a	12.6	6.2	7.9	7.8	4.6	5.8
Baling and storage ^b	3.5	3.5	3.5	–	–	–
Auxiliary energy requirements ^c	36.1	41.6	44.2	8.1	8.1	8.1
Hard-coal combustion (pre-combustion) ^d	–	–	–	44.2	32.0	33.9
Hard-coal combustion (combustion-related) ^e	–	–	–	306.8	308.4	326.2
CH ₄ and N ₂ O emissions from composting ^f	–	–	–	68.3	47.4	43.0
Mineral-fertilizer substitution ^g	–	–	–	– 81.4	– 51.4	– 45.0
Total GHG emissions		E_{HTC}			$E_{Reference}$	
kg CO ₂ e/t FM input ^h	52.2	51.3	55.5	353.8	349.2	372.0
t CO ₂ e/a ⁱ	3,844	3,878	4,517	26,074	26,410	30,266
Difference		$E_{Reference} - E_{HTC}$			–	
kg CO ₂ e/t FM input ^h	301.6	298.0	316.5	–	–	–
t CO ₂ e/a ^h	22,230	22,532	25,749	–	–	–

Notes: Values rounded. – Not applicable.

^a Own calculation, based on the diesel requirements for transportations from Table S.2 and the diesel emissions from Table S.4.^b Own calculation, based on the diesel and electricity requirements for baling and storage from Table S.2 and the emissions from diesel and electricity (mix Germany) from Table S.4.^c Own calculation, based on the auxiliary diesel, natural-gas, and electricity requirements from Table S.2 and the respective emissions from Table S.4. For HTC-coal drying, the urban HTC scenario uses electricity from the BSR waste-incineration plant located at the site of the HTC plant, while the rural-urban HTC scenario uses electricity from hard coal combusted at the Reuter West CHP plant. In all other cases, electricity refers to the German mix.^d Own calculation, based on the usable heat and electricity from HTC coal (Table S.2) and the pre-combustion emissions resulting from the use of hard coal, both heat- and electricity-related (Table S.4).^e Own calculation, based on the usable heat and electricity from HTC coal (Table S.2) and the combustion-related emissions resulting from the use of hard coal, both heat- and electricity-related (Table S.4).^f Own calculation, based on the composting-related GHG emissions from Table S.4 and the shares of leaves and grass cuttings from Table 1.^g Own calculation, based on the emission savings from compost soil application due to the replacement of mineral fertilizers (Table S.4), combined with the shares of leaves and grass cuttings from Table 1.^h Own calculation.ⁱ Own calculation, multiplying the values in kg CO₂e/t FM input by the biomass inputs in t FM/a (Table 1), and dividing by 1,000.

3. Data

The data for the GHG mitigation potential and carbon abatement costs are calculated with the help of Excel spreadsheets. Thus, most of the values are rounded.

3.1. GHG mitigation potential

A summary of the GHG emissions entering E_{HTC} and $E_{Reference}$ is displayed in Table 2, along with the GHG mitigation potential of HTC coal. The data are presented in detail in Section S.3.

3.2. Carbon abatement costs

In addition to the GHG mitigation potential (Table 2), the AC calculation is based on the following costs and revenues (€/a) of the HTC and reference scenarios (Tables 3 and 4).

3.2.1. Costs

Our cost inventory covers capital-related costs, transportation costs, preparation, baling, and storage costs, consumption-related costs, as well as operation-related costs.

3.2.1.1. Capital-related costs. The investment costs for an HTC plant are €15,000,000 (SunCoal, unpublished data). Moreover, the investment costs for the biomass CHP plant in the urban HTC scenario amount to €16,958,000. This value is based on Obernberger and Thek (2004), who provide an economic evaluation of a Danish biomass CHP plant of similar size.

The annual capital-related costs for composting are derived from the

specific capital costs of 9 €/t FM input (van Haaren et al., 2010: 2654), multiplied by the biomass inputs (Table 1).

For the Reuter West CHP plant, no capital-related costs occur since its two blocks have been in existence since 1987 and 1989, respectively (Vattenfall, 2017), and are assumed to be fully written off. Thus, the reduction of hard-coal combustion in the urban HTC scenario due to HTC-coal mono-firing in the new biomass CHP plant has no impact on the installed capacity at Reuter West. Moreover, in the rural-urban and rural HTC scenarios, HTC-coal co-firing in substitution for hard coal renders any additional capacity installation superfluous. We further assume that no retrofitting of the Reuter West CHP plant is required for HTC-coal co-firing.

3.2.1.2. Transportation costs. The annual costs for the transportation of the biomass, HTC coal, and compost in the different scenarios are derived in Medick et al. (2017: Tables 5–10), who also provide the detailed transportation distances. We assume transportation costs of €71.7 per hour (h) (Leible, 2003: 257) – including those for diesel (cf. Table S.2) – for a semi-trailer truck with a load capacity of 40 m³ and a maximum cargo load of 20 t (Zentner, 2013: 12; Table S.3), an average speed of 50 km/h, 0.6 h for loading, 0.2 h for unloading, and 0.7 h for the journey from and to the truck stations and all maneuvering activities (Leible, 2003: 258).

3.2.1.3. Preparation, baling, and storage costs. For biomass preparation in the HTC scenarios, we ascribe 15.0 €/t FM input (SunCoal, unpublished data), including the costs for electricity (cf. Table S.2). The residues left behind after preparation are disposed of at 4.9 €/t FM input (SunCoal, unpublished data). The total annual costs for baling (including coverage with foil) and storage in the HTC scenarios can be

Table 3

Annual costs and revenues in the HTC scenarios.

Sources: Own calculations.

	Value			Urban HTC scenario	Rural-urban HTC scenario	Rural HTC scenario
	Urban	Rural-urban	Rural			
	€/t FM input			€/a		
	(1)			(2)	(3)	(4)
Capital-related costs	-	-	-	2,900,393	1,361,346	1,361,346
HTC plant ^a	-	-	-	1,361,346	1,361,346	1,361,346
Biomass CHP plant ^a	-	-	-	1,539,047	-	-
Transportation costs	-	-	-	2,236,355	1,282,762	1,775,822
Biomass ^b	-	-	-	2,236,355	1,282,762	1,550,610
HTC coal ^b	-	-	-	-	-	225,212
Preparation, baling, and storage costs	-	-	-	1,895,345	1,933,542	2,047,775
Biomass preparation (including electricity) ^c	15.0	15.0	15.0	1,105,517	1,134,309	1,220,414
Residue disposal ^c	4.9	4.9	4.9	361,136	370,541	398,669
Baling and storage ^d	-	-	-	428,692	428,692	428,692
Consumption-related costs	-	-	-	710,907	471,877	727,933
Electricity (for HTC-coal drying) ^c	1.62	1.58	4.28	119,670	119,670	347,897
Natural gas ^c	1.03	1.00	0.93	75,557	75,557	75,557
Diesel fuel ^c	0.34	0.34	0.34	24,913	25,562	27,502
Fresh water ^c	0.05	0.05	0.03	3,906	3,906	2,736
Wastewater treatment ^c	1.5	1.5	1.5	110,552	113,431	122,041
HTC-coal combustion ^c	-	1.77	1.87	376,310	133,752	152,199
Operation-related costs	-	-	-	831,580	423,475	455,621
Personnel ^c	2.8			206,363	211,738	227,811
Service and maintenance ^c	2.8			206,363	211,738	227,811
HTC-coal combustion ^f	-	-	-	418,854	-	-
Revenues	-	-	-	2,510,992	-	-
Sales of electricity ^c	7.73	-	-	569,503	-	-
Sales of heat ^c	26.34	-	-	1,941,489	-	-
Total annual net costs (C _{HTC})				6,063,588	5,473,003	6,368,498
				Urban HTC scenario	Rural-urban HTC scenario	Rural HTC scenario
Abatement Costs (AC) ^g	€/t CO ₂ e			162.7	76.1	77.2

Notes: Values rounded. - Not applicable.

^a Investment costs of €15,000,000 for an HTC plant (SunCoal, unpublished data) and of €16,958,000 for the biomass CHP plant (Oberberger and Thek 2004: Tables 4.3 and 4.5; without credit costs), multiplied by the annuity factor *AF* (Section 2.3).^b Medick et al. (2017: Tables 5-7).^c Column 1: Table S.5. Columns 2-4: Multiplying the respective value from column 1 by the respective FM biomass input (Table 1).^d Table S.6.^e Urban HTC scenario: 65,495 €/a electricity, 100,815 €/a additional heat generation costs, 110,000 €/a general consumption costs, and 100,000 €/a for ash disposal (Oberberger and Thek 2004: Tables 4.4 and 4.6), where the electricity costs are obtained by multiplying 2,339,092 kWh/a (Oberberger and Thek 2004: Table 4.2) by the 2016 average end-of-month base-load electricity spot-market price of 0.028 €/kWh (EEX 2017). Rural-urban and rural HTC scenarios: Column 1: Multiplying 1.28 €/MWh at the Reuter West CHP plant (Table S.7) by the usable energy from HTC coal (Table S.2), dividing it by 1,000, and multiplying it by the factor 30/20 to correct for the different lower heating values of hard coal (30 MJ/kg) and HTC coal (20 MJ/kg). Columns 3 and 4: Multiplying the respective value from column 1 by the respective FM biomass input (Table 1).^f 203,854 €/a for personnel and 215,000 €/a for maintenance (Oberberger and Thek 2004: Tables 4.4 and 4.6).^g Own calculation, based on Eq. (1) and the corresponding data from Tables 2 to 4.

found in Table S.6.

In the reference scenarios, the prepared biomass is composted without storage. The costs for biomass preparation are covered under consumption- and operation-related costs.

3.2.1.4. Consumption-related costs. Consumption-related costs refer to the expenditures for auxiliary electricity, heat (natural gas), and diesel outlined in Table S.2 and not yet covered under transportation or preparation, baling, and storage costs, as well as for any other inputs.

As summarized in Table S.5, we use the 2014–2016 average prices for electricity and natural gas for industrial customers of €0.0814 per kilowatt hour (kWh) (Statista, 2017a) and 0.03 €/kWh (Statistisches Bundesamt, 2017a: 22), respectively, and the April 2016–April 2017 average diesel price of 1.12 €/liter (Statista, 2017b). For HTC-coal drying in the urban and rural-urban HTC scenarios, we replace the electricity price by the 2016 average end-of-month base-load electricity spot-market price of €28 per megawatt hour (MWh) (EEX, 2017) to reflect synergy effects from the co-location of the HTC plant with the

BSR waste-incineration plant and the Reuter West CHP plant, respectively.

To run the HTC process, 1,800 m³/a fresh water are used (SunCoal, unpublished data). According to Statistisches Bundesamt (2017b), the price of fresh water is 2.17 €/m³ in Berlin and 1.52 €/m³ in the federal state of Brandenburg. The wastewater from the HTC process, in turn, is treated at 1.5 €/t FM input (SunCoal, unpublished data).

In the urban HTC scenario, the consumption-related costs for HTC-coal mono-firing are derived from Oberberger and Thek (2004), with electricity priced at 28 €/MWh (EEX, 2017) to allow for synergies with the BSR waste-incineration plant. The consumption-related costs for HTC-coal co-firing, in turn, are based on 1.28 €/MWh of variable operating costs applied for the Reuter West CHP plant (Table S.7).

In the reference scenarios, composting (including biomass preparation) is associated with specific variable costs of 11 €/t FM input (van Haaren et al., 2010: 2654). These are transformed into annual costs of 810,713 €/a (urban reference scenario), 831,827 €/a (rural-urban reference scenario), and 894,970 €/a (rural reference scenario)

Table 4

Annual costs and revenues in the reference scenarios.

Sources: Own calculations.

	Value			Urban reference scenario	Rural-urban reference scenario	Rural reference scenario
	Urban	Rural-urban	Rural			
€/t FM input	€/a					
(1)	(2)			(3)	(4)	
Capital-related costs for composting ^a	9.00	9.00	9.00	663,310	680,585	732,249
Transportation costs	–	–	–	1,531,054	930,140	1,245,803
Biomass ^b	–	–	–	13,22,254	800,074	11,25,048
Compost ^b	–	–	–	208,800	130,066	120,755
Consumption-related costs	–	–	–	1,838,286	1,543,218	1,745,228
Composting ^c	–	–	–	170,250	174,684	187,944
Hard-coal combustion ^d	22.63	18.10	19.14	16,68,037	13,68,534	15,57,285
Operation-related costs	–	–	–	974,356	657,143	707,027
Composting ^e	–	–	–	640,463	657,143	707,027
Hard-coal combustion ^f	4.53	–	–	333,893	–	–
Revenues	–	–	–	2,559,409	53,388	49,566
Sales of compost ^g	1.16	0.71	0.61	85,705	53,388	49,566
Sales of electricity ^h	14.81	–	–	10,91,548	–	–
Sales of heat ^h	18.75	–	–	13,82,155	–	–
Total annual net costs ($C_{Reference}$)				2,447,598	3,757,698	4,380,740

Notes: Values rounded. - Not applicable.

^a Column 1: van Haaren et al. (2010: 2654). Columns 2–4: Multiplying the value from column 1 by the FM biomass input of the corresponding HTC scenario (Table 1).^b Medick et al. (2017: Tables 8–10).^c 21% of 810,713 €/a (urban reference scenario) | 831,827 €/a (rural-urban reference scenario) | 894,970 €/a (rural reference scenario) (Section 3.2.1).^d Column 1: 19.61 €/MWh (Table S.7) multiplied by the respective usable energy from HTC coal (Table S.2) and divided by 1,000. Columns 2–4: Multiplying the respective value from column 1 by the FM biomass input of the corresponding HTC scenario (Table 1).^e 79% of 810,713 €/a (urban reference scenario) | 831,827 €/a (rural-urban reference scenario) | 894,970 €/a (rural reference scenario) (Section 3.2.1).^f Column 1: 3.93 €/MWh (Table S.7) multiplied by the usable energy from urban HTC coal (Table S.2) and divided by 1,000. Column 2: Multiplying the value from column 1 by the FM biomass input of the urban HTC scenario (Table 1).^g Column 1: 11.63 €/t compost (BGK, 2017: 6) multiplied by the respective compost share of 40% for leaves and 18% for grass cuttings (Table S.1) and weighted by the respective shares of leaves and grass cuttings in the FM biomass (Table 1), minus the respective compost transportation costs (Medick et al., 2017: Tables 8–10) divided by the FM biomass input of the corresponding HTC scenario (Table 1). Columns 2–4: Multiplying the respective value from column 1 by the FM biomass input of the corresponding HTC scenario (Table 1).^h Column 1: Table S.7. Columns 2–4: Multiplying the respective value from column 1 by the FM biomass input of the corresponding HTC scenario (Table 1).

when multiplied by the respective biomass inputs (Table 1). A share of 21% thereof refers to consumption-related costs (van Haaren et al., 2010: 2654), including those for electricity and diesel (cf. Table S.2).

The consumption-related costs for hard-coal combustion at the *Reuter West* CHP plant amount to 19.61 €/MWh (Table S.7), comprising 1.28 €/MWh of variable operating costs and approximately 18.33 €/MWh of fuel costs. Note that we do not take into account any carbon costs in the calculation of carbon abatement costs (cf. Marcantoni and Ellerman, 2015).

3.2.1.5. Operation-related costs. Operation-related costs mainly address expenses for personnel and service-and-maintenance efforts. In the HTC scenarios, they amount to 5.6 €/t FM input for the operation of an HTC plant (SunCoal, unpublished data). Costs of similar magnitude accrue for HTC-coal mono-firing (Oberberger and Thek, 2004). Operation-related costs for HTC-coal co-firing at the *Reuter West* CHP plant in the rural-urban and rural HTC scenarios are not applicable since identical costs occur in the corresponding reference scenarios.

79% of the annual variable costs of composting refer to service-and-maintenance efforts (van Haaren et al., 2010: 2654). The operation-related costs for the *Reuter West* CHP plant in the urban reference scenario amount to 3.93 €/MWh (Table S.7).

3.2.2. Revenues

Revenues that differ between a given HTC scenario and its reference case and, thus, do not drop out of the AC calculation include sales of electricity and heat in the urban scenario. Despite the same amount of usable energy in the urban HTC and reference scenarios, the quantities

of heat and electricity from HTC-coal and hard-coal combustion are not identical. This is due to differences in the thermal and electrical conversion efficiencies between the biomass CHP plant in the urban HTC scenario and the *Reuter West* CHP plant in the urban reference scenario (Section S.3.2). Any electricity sales are rewarded with the spot-market price of 28 €/MWh (EEX, 2017) and heat sales with the heat retail price of 30 €/MWh (Gores et al., 2013: 23).

In the reference scenarios, we further consider revenues from the sale of compost. They reflect the production costs for mineral fertilizers that are saved by the use of compost and are based on the assumption that farmers are willing to pay the same for compost as for the nutrient-equivalent amount of mineral fertilizers, after accounting for compost transportation costs. In 2016, the average nutrient value of compost reached 11.63 €/t compost (BGK, 2017: 6).

4. Results and discussion

This section presents and discusses the results for the GHG mitigation potential and the carbon abatement costs of HTC coal. It also provides sensitivity checks for key assumptions.

4.1. GHG mitigation potential

The HTC scenarios are associated with relatively modest total specific GHG emissions in the range of 51.3–55.5 kg CO₂e/t FM input, while those of the reference scenarios amount to 349.2–372.0 kg CO₂e/t FM input (Table 2). The single most important driver of the GHG emissions in the reference scenarios is hard-coal combustion, with

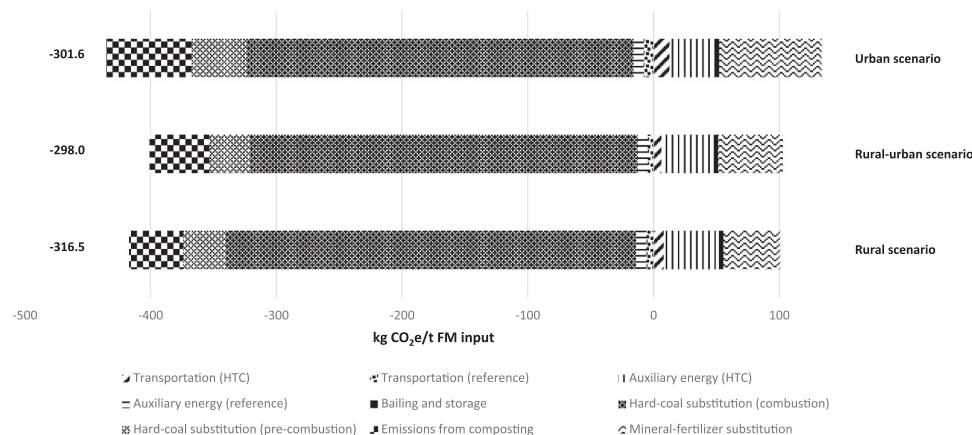


Fig. 2. HTC life-cycle emissions net of reference emissions.

Source: Table 2, with inverted signs for GHG emissions from the reference scenarios. Notes: Each scenario is based on a different annual FM biomass input (Table 1). Values rounded.

combustion-related emissions of 306.8–326.2 kg CO₂e/t FM input and pre-combustion emissions of 32.0–44.2 kg CO₂e/t FM input (Table 2). The reference scenarios' emission savings from the use of compost to replace mineral fertilizers are slightly outweighed by the CH₄ and nitrous-oxide (N₂O) emissions from composting and the emissions from transports and auxiliary energy requirements (Table 2).

Assessed against the respective reference case, the HTC scenarios lead to substantial net GHG savings ($E_{\text{Reference}} - E_{\text{HTC}}$): 301.6 kg CO₂e/t FM input in the urban scenario, 298.0 kg CO₂e/t FM input in the rural-urban scenario, and 316.5 kg CO₂e/t FM input in the rural scenario (Table 2; Fig. 2). These are largely driven by the substitution of hard coal. Despite the common assumption of HTC-coal co-firing, the rural HTC scenario performs better than the rural-urban HTC scenario since it substitutes for a greater amount of hard coal. The reason is that the rural HTC coal is entirely derived from low-moisture grass cuttings (Section S.3.1), leaving it with a higher energy content than the rural-urban HTC coal (Table S.2). While the urban HTC coal has the lowest energy content, the favorable conversion efficiency of the biomass CHP plant (92% versus 72% for the Reuter West CHP plant, Section S.3.2) means that the urban HTC scenario saves nearly as many GHG emissions as the rural HTC scenario.

Further taking account of each scenario's annual biomass input (Table 1), the GHG mitigation potential of HTC coal reaches 22,230 t CO₂e/a in the urban scenario, 22,532 t CO₂e/a in the rural-urban scenario, and 25,749 t CO₂e/a in the rural scenario (Table 2). Thus, in aggregate, the three HTC scenarios can mitigate 70,511 t CO₂e per year.

70,511 t CO₂e/a corresponds to about 1.6% of the GHG savings of 4.3 million t CO₂e/a required to reduce Berlin's GHG emissions from the 2005 level of 21.9 million t CO₂e/a to the 2020 target of 17.6 million t CO₂e/a (Suck et al., 2011: 1). The aggregated GHG mitigation potential is comparable to the emission savings of 67,874 t CO₂e/a reached by third-party contracting to increase the energy efficiency of public buildings in Berlin (Suck et al., 2011: 87). However, it is much smaller than the mitigation potential of many other measures. For example, the replacement of traditional boilers by small, decentral CHP stations could possibly save up to 280,000 t CO₂e/a (Suck et al., 2011: 84). Even greater mitigation potentials could be achieved by improvements to the energy efficiency of private buildings (Suck et al., 2011).

4.2. Carbon abatement costs

The urban scenario leads to carbon abatement costs, AC, of 162.7 €/t CO₂e, the rural-urban scenario to 76.1 €/t CO₂e, and the rural scenario to 77.2 €/t CO₂e (Table 3).

To understand the discrepancies between the urban scenario, on the one hand, and the rural-urban and rural scenarios, on the other hand,

we disaggregate the AC into their single cost components (Fig. 3): The move from the reference scenarios to the HTC scenarios increases the capital-related costs and the transportation costs. Unlike the urban HTC scenario, however, the rural-urban and rural HTC scenarios profit from the possibility of co-firing the HTC coal in an existing CHP plant (Section 2.1), which reduces their capital requirements. Moreover, they apply simpler logistics concepts than the urban HTC scenario (Section 2.1) and are, thus, associated with lower transportation costs. A major driver of the AC in all three scenarios is the costs incurred for biomass preparation, baling, and storage, while forgone revenues (mainly from the sale of compost) are the smallest contributor to the abatement costs. A cost-reducing component of the AC is the lower consumption- and operation-related costs of the HTC scenarios compared to their reference cases.⁶ The reduction in the consumption-related costs is lowest in the rural scenario since it misses the possibility of electricity self-supply for HTC-coal drying (cf. Sections 2.1 and 3.2.1).

Since the AC calculation abstracts from any carbon costs, the abatement costs coincide with the CO₂ price necessary to render the HTC scenarios more profitable than their reference cases. Thus, at the current CO₂ prices of 5 €/t CO₂ (end of July 2017) to nearly 17 €/t CO₂ (end of July 2018) (EEX, 2018), none of the HTC scenarios is economically viable. However, the current CO₂ prices do not fully internalize the damage costs imposed on society by unmitigated GHG emissions. The size of the damage costs (or social costs of carbon) is highly controversial since they are based on many unknowns (e.g., van den Bergh and Botzen, 2014; UBA, 2014; Krewitt and Schlomann, 2006). However, if we apply the lower bound of 125 US\$/t CO₂ (about 107 €/t CO₂ at the 27 July 2018 exchange rate) as derived in the meta study by van den Bergh and Botzen (2014), our rural-urban and rural HTC scenarios clearly become socially desirable.

The AC in the rural-urban and rural scenarios compare well with those obtained by Erlach et al. (2011) for HTC coal from biodegradable waste used to substitute for bituminous coal, 81.28 €₂₀₀₉/t CO₂e. While the AC in the urban scenario are higher, they come relatively close to the 115.75–135.14 €₂₀₀₉/t CO₂e for HTC coal from poplar wood chips (Erlach et al., 2011).

All scenarios' AC are lower than the 190 €/t CO₂e associated with biogas generated from biodegradable waste to replace electricity and heat from a modern coal power plant (Hennig and Gawor, 2012: Figure 8). The carbon abatement costs for the other bioenergy pathways in Hennig and Gawor (2012: Figure 8), such as direct combustion of

⁶ However, other than in the HTC scenarios, the consumption- and operation-related costs in the reference scenarios include the costs for biomass preparation (Section 3.2.1).

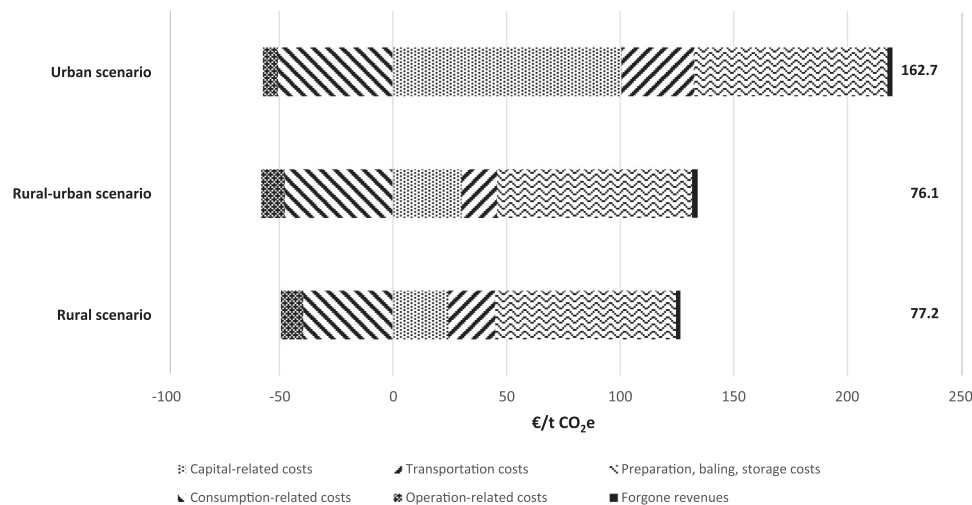


Fig. 3. Breakdown of carbon abatement costs.

Sources: For each cost category, the values refer to the difference in costs between each HTC and reference scenario in €/a as obtained from Tables 3 and 4, divided by the respective GHG mitigation potential, $E_{\text{Reference}} - E_{\text{HTC}}$ (t CO₂e/a), from Table 2. Note: Values rounded.

forestry residues or biogas from corn (maize) silage, reach even 240–510 €/t CO₂e. Similarly, the carbon abatement costs for biogas from corn and from mixtures of corn and cattle slurry in Brandenburg, Germany, range from 288 to 674 €/t CO₂e without accounting for opportunity costs related to land use; if considering opportunity costs, then they amount to 459–1135 €/t CO₂e (Scholz et al., 2011).

Compared to non-biomass sources of renewable energy, the AC in our study fall between the implicit carbon prices of wind and solar energy in Germany during the early phase of their public promotion. For example, Marcantonini and Ellerman (2015: Table 8) find that the 2006–2010 average implicit carbon price, which is largely equivalent to carbon abatement costs, amounted to 57 €/2011/t CO₂ for wind energy and 552 €/2011/t CO₂ for solar energy – if remunerations to generators in the form of feed-in tariffs granted by Germany's Renewable Energy Act are taken into account. Even if learning effects are included, the average implicit carbon prices still stand at 48 €/2011/t CO₂ for wind and 306 €/2011/t CO₂ for solar energy (Marcantonini and Ellerman, 2015: 228). However, the costs for solar energy should be considered as an upper bound since the feed-in tariffs for solar energy have been drastically reduced since 2012, albeit only for new installations (Marcantonini and Ellerman, 2015).

4.3. Sensitivity analysis

We perform sensitivity checks for the HTC-process efficiency, the costs of the biomass CHP plant, and the discount rate i (Table S.8). Moreover, we indicate how the HTC of green waste will perform as a GHG mitigation measure if HTC coal substitutes for lignite or natural gas rather than hard coal, and if we compare it to other GHG mitigation technologies.

HTC is associated with considerable process water, which contains a vast amount of dissolved organic and inorganic compounds (e.g., Funke and Ziegler, 2010). Potential increases in the efficiency of the HTC process can be achieved by using the carbon dissolved in the process water for energy generation. This can be done by anaerobically digesting the process water to produce biogas (e.g., Wirth et al., 2012) or by recirculating the process water to increase the carbon yield of HTC coal (e.g., Stemann et al., 2013b). While Wirth et al. (2012) provide conditions for a reduction in the HTC-coal production costs if the biogas from the anaerobic digestion of the process water is used as auxiliary energy in the HTC process, we focus on process-water recirculation. In line with Stemann et al. (2013b), who find significant increases in the carbon and energy densities of HTC coal, but only slight rises in the

HTC-coal mass yield, we increase the heating value of HTC coal at given HTC-coal outputs. In particular, we assume that the lower heating value of HTC coal increases by 5% (cf. Stemann et al., 2013b: Table 4), from 20 megajoule (MJ) per kg (Section S.3.2) to 21 MJ/kg. This raises the GHG mitigation potential of HTC coal by nearly 6% and lowers the AC by 7.7–9.2% (Table S.8), keeping the investment costs for an HTC plant constant. Further adding in the corresponding reduction in fresh-water use and wastewater-treatment costs (75%, cf. Stemann et al., 2013b), the AC can be lowered by 10–14% in total (Table S.8).

One of the main drivers of the higher AC in the urban scenario is the construction of a new biomass CHP plant for HTC-coal mono-firing. The biomass CHP plant raises the capital-related costs and is also associated with higher consumption- and operation-related costs than the Reuter West CHP plant used for HTC-coal co-firing (Table 3). Aligning the consumption- and operation-related costs of the biomass CHP plant with those of the Reuter West CHP plant (50% decrease), the AC of the urban scenario can be reduced by 11% (Table S.8). Additionally cutting the capital-related costs of the biomass CHP plant by the same 50%, a 32.3% decrease in the AC can be achieved (Table S.8). While this reduction brings the AC of the urban scenario, about 110 €/t CO₂e, closer to the lower bound of the social costs of carbon (cf. van den Bergh and Botzen, 2014), it leaves the urban scenario's ranking within the three scenarios unaffected.

As expected, our results are sensitive to the assumed discount rate, $i = 6.5\%$. For $i = 0\%$, the AC are lowered by 30.8–36.0%; $i = 10\%$ increases the AC by 20.2–23.6% (Table S.8).

While we leave the detailed calculations for future research, another critical factor is the type of fossil fuel chosen as reference. In addition to hard coal, lignite and natural gas are relevant fossil fuels for stationary combustion in Germany. Replacing hard coal by lignite, a more emission-intensive fuel, the HTC scenarios will likely be associated with greater GHG mitigation potentials and lower AC. The opposite should hold for the cleaner natural gas.

As outlined in the introduction, biogenic waste has unfavorable characteristics for direct biomass combustion and, depending on the feedstock, anaerobic digestion. This suggests that HTC will perform better as a GHG mitigation technology than these two alternatives for the green waste considered in our study. This hypothesis is also supported by literature results: As discussed in Section 4.2, the abatement costs for the anaerobic digestion of biodegradable waste obtained by Hennig and Gawor (2012) exceed the AC in our scenarios. Erlach et al. (2011) and Stemann et al. (2013a) further find that the production costs of HTC-coal pellets compare to those of wood pellets if biodegradable

waste is available at zero cost. Notwithstanding these results, future research should provide a comprehensive assessment of the GHG mitigation potentials and costs of different treatment technologies for green waste.

5. Conclusions and policy implications

Our environmental and economic assessment has revealed that the production of HTC coal from leaves and grass cuttings for renewable-energy generation in the metropolitan region of Berlin, Germany, is an effective GHG mitigation measure, with positive GHG mitigation potentials in all three scenarios. However, the carbon abatement costs vary strongly. While they remain below 80 €/t CO₂e in the rural-urban and rural scenarios, they are more than double this size in the urban scenario. Thus, to realize the GHG mitigation potential of HTC coal in the most efficient way, the logistics concept should be as simple as possible and, most importantly, HTC coal should be co-fired in existing CHP plants to save the investment costs for new CHP plants dedicated to HTC-coal mono-firing. Moreover, the feedstocks should be available at zero costs, using HTC as a combined GHG-mitigation and waste-management technology.

Our results can be transferred to many other major cities and regions where the just-stated favorable conditions for HTC-coal production and co-firing prevail. All it takes are sufficient amounts of green waste, currently treated under suboptimal waste-management practices, in close proximity to existing coal-fired power plants. Thus, HTC can be particularly attractive for densely populated areas, which tend to have high carbon footprints and high waste potentials. In lower-income countries, the abatement costs of HTC coal could be generally much lower than in our case study for Germany due to the availability of cheaper labor.

In Germany, HTC-coal co-firing in existing coal-fired power plants could render the fossil-coal phase-out more climate-friendly. Moreover, it could help to reach the German government's target to decrease the country's 2030 GHG emissions by 55% below the 1990 level (BMWi and BMU, 2010), i.e. by about 688 million t CO₂e. Applying the lower net GHG savings of about 300 kg CO₂e/t FM input (Table 2) to the green-waste potentials in Germany (about 2.3 million t dry matter per year, Brosowski et al., 2016: 267), HTC coal could mitigate 1.5–2.8 million t CO₂e/a (at 46% and 25% dry-matter contents of fresh green waste, Table S.1). Thus, it could contribute 0.2–0.4% to the targeted emission reduction. Since green waste is only a fraction of biogenic municipal waste (Brosowski et al., 2016), the contribution of HTC coal could be raised by more than factor ten if it performs similarly for other types of biogenic waste.

However, at the current CO₂ prices, the GHG mitigation potential of HTC coal will not be unleashed. With HTC-coal co-firing in the rural-urban and rural scenarios attaining carbon abatement costs below the lower bound of the social costs of carbon (Section 4.2) and with cost-reducing factors identified for all scenarios in our sensitivity analysis, it could be considered to publicly support HTC-coal production as an early-phase technology.

For example, Germany's Renewable Energy Act could be used to directly support HTC-coal co-firing. Moreover, municipalities can use existing regulatory frameworks, such as the possibility to include environmental criteria in their public tenders (green public procurement), to establish lower-emission waste-management practices. In this way, green waste could be redirected from composting into HTC-coal production. More generally, the carbon prices should better reflect the damage costs of unmitigated climate change. Higher carbon prices could be realized, for example, by an increase in the price of emission allowances in the European Union Emissions Trading System or by a floor price for carbon emissions as currently discussed in Europe.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2018.08.033.

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